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# **THE SPECTRUM OF HM SAGITTAE: A PLANETARY NEBULA EXCITED BY A WOLF-RAYET STAR**

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The Spectrum of HM Sagittae: A Planetary Nebula  
Excited by a Wolf-Rayet Star

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ABSTRACT

Eight image tube spectrograms of HM Sagittae were obtained during July and August, 1977. More than 70 emission lines, including several broad emission features, have been identified. An analysis of the spectra indicates that HM Sge is a planetary nebula excited by a Wolf-Rayet star. The most conspicuous Wolf-Rayet feature is that attributed to a blend of C III at  $4650 \text{ \AA}$  and He II at  $4686 \text{ \AA}$ .

## INTRODUCTION

A new emission line object with continuous and emission line spectral features was reported by Dokuchaeva (1976), based on an objective prism plate. According to that report, the magnitude of this stellar object rose from  $16^m$  to  $11^m$  between April and September, 1976. Examination of the Palomar Sky Survey prints for 1950 showed an object of about  $17^m$  (O-chart) with a remarkably red color. The magnitude varied between  $11^m$  and  $12^m$  during the interval September 1975 to July 1976. A spectrum published by Stover and Sivertsen (1977) showed the object to have emission lines characteristic of a planetary nebula in the region  $\lambda\lambda 4470-9500$ . A spectrum similar to this was reported by Bopp (1977) and by McCracken (1977). The 1950.0 coordinates for this object, HM Sagittae, are:  $\alpha=19^h 39^m 41.40^s, \delta=+16^\circ 37' 33''.1$  (Shao, 1977). A radio source was detected at this position by Feldman (1977), who suggested that HM Sge may be an embryonic planetary nebula.

## OBSERVATIONS

HM Sge was observed on four nights with the Goddard 91-cm reflector and Cassegrain spectrograph equipped with an RCA C33011 image intensifier having a S-20 photocathode. The dispersion was approximately  $82\text{\AA}/\text{mm}$  in the first-order red and  $41\text{\AA}/\text{mm}$  in the second-order blue, with a resolution of approximately 2 to 3  $\text{\AA}$  in the second-order blue. The dates of observation, exposure times, plates used, and wavelength ranges for the spectrograms are listed in Table 1. The positions of the

emission lines were measured on a small Gaertner measuring machine; their identifications and qualitative estimates of strength are listed in Tables 2(a) and 2(b). All spectrograms listed in Table 1 were traced on a Joyce-Loebl microdensitometer to obtain measurements of photographic density as a function of position along the direction of dispersion. Tracings of the spectrograms for Aug. 18-19 are shown in Figs. 1(a) and 1(b). Conversion from density to intensity (incident on the plate) has not yet been accomplished, although the plate for each night's observations was sensitometrically calibrated by imaging a Kodak 21-step wedge onto the same plate that contained the spectrograms.

The first spectrograms were exposed through a Schott GG-13 (2 mm) filter so as to block out the second-order blue spectrum. Examination of the spectrograms showed an emission line spectrum superimposed on a continuum completely free of absorption lines. This suggested that subsequent observations should be made at the highest dispersion possible with the available gratings and camera, and that two different grating tilts should be used to obtain full wavelength coverage in the visible region of the spectrum. One of these tilts involved mixed first-order red and second-order blue. At least one exposure at each grating tilt was made during each of the subsequent observing sessions. The spectrograms were not spectrophotometrically calibrated by taking spectra of faint standard stars because of the variability of extinction and lack of observing time.

## DISCUSSION

HM Sge had a stellar appearance each night on which it was observed, but this undoubtedly was influenced by the 3 to 5 arc-sec seeing prevalent on all four nights. The guided (unwidened) spectra consist of two components: (a) an emission line spectrum characteristic of planetary nebulae and (b) an underlying continuum without any absorption lines but with several wide emission features characteristic of a Wolf-Rayet star of type WC. Approximately 100 separate emission features have been measured; 76 have been definitely identified (six of them due to Hg night sky contamination), 3 have been observed in other high excitation planetaries but not identified, and the remainder are weak and either unidentified or doubtful.

The Balmer lines of hydrogen from  $H_\alpha$  to  $H_{20}$  are present. The [N II] 6548, 6584 $\overset{\circ}{\text{A}}$  lines are well resolved from  $H_\alpha$  on the short exposures. Prominent lines of He I, [O I], [O II], [O III], [Ne III], and [Ar III] are obvious. Weaker lines of He II, Si II, [S II], [S III], [Cl III], [Ar IV], and several others are detectable. The [O II] 3726, 3729 $\overset{\circ}{\text{A}}$  doublet is present and is appropriately exposed and adequately resolved on one of the spectrograms to show that the ratio of intensities  $I(3729)/I(3726) \ll 1$ . This ratio qualitatively indicates a very high electron density (cf. Eissner, et al., 1969) similar to that of IC 4997. The [O II] 7320, 7330 $\overset{\circ}{\text{A}}$  doublet is clearly present on the appropriate spectrograms for each of the four nights.

The [S II] 6717, 6731  $\text{\AA}$  doublet (which could have been used to derive an electron density) is conspicuously absent, but the [S II] 4068, 4076  $\text{\AA}$  doublet is present. This anomaly also suggests a high electron density (Aller and Liller, 1968, pp 528-9) in agreement with that indicated by the [O II] I(3729)/I(3726) ratio.

An electron temperature,  $T_e \geq 10^4 \text{ K}$ , is indicated by the presence of the [N II] 5755  $\text{\AA}$  and [O III] 4363  $\text{\AA}$  lines. Collisional de-excitation in a very high density nebula will, however, affect the electron temperatures derived from the [N II] 5755/(6548+6584) and [O III] 4363/(4959+5007) intensity ratios (Osterbrock, 1974). The electron temperature cannot be much in excess of  $10^4 \text{ K}$  because the He II 4686  $\text{\AA}$  line is completely undetectable in the nebular spectrum. Evidence for a moderately high excitation nebula is provided by the nearly equal intensity of the  $H_\beta$  and [O III] 5007  $\text{\AA}$  lines and by the presence of [Ne III], [Fe II], and [Ar IV] lines. Contamination of the [O III] 4363  $\text{\AA}$  line by the Hg I 4358  $\text{\AA}$  line prevents a direct comparison with  $H_\gamma$ , but visual comparison shows that the intensity of the [O III] 4363  $\text{\AA}$  line is somewhat lower than that of  $H_\gamma$ .

Several broad emission features are present which identify the exciting star as a Wolf-Rayet of type WC. The strongest Wolf-Rayet feature is that of C III 4650  $\text{\AA}$  and He II 4686  $\text{\AA}$  which stands out clearly in Figure 1(a). Weaker WR features are present for He II 5411  $\text{\AA}$  - O V 5471  $\text{\AA}$  and possibly for the O III and O IV feature at 3400  $\text{\AA}$ . There

are broad emission features (pedestals) under the hydrogen lines from  $H_\alpha$  to  $H_\epsilon$ . The pedestals under these hydrogen lines and the He II 5411, 4542, and 4200  $\text{\AA}$  lines can be attributed to the Pickering series of He II in the spectrum of the Wolf-Rayet star (Aller, 1968, p. 344). A Wolf-Rayet feature of CII at 6580  $\text{\AA}$  may also contribute to the apparent pedestal under the  $H_\alpha$  and [N II] lines. The He II 4686  $\text{\AA}$  line of the Fowler series together with C III 4650  $\text{\AA}$  constitutes the rather broad, flat-topped emission feature shown in Figure 1(a) and is characteristic of a Wolf-Rayet star, but with the [Fe III] 4658  $\text{\AA}$  and 4701  $\text{\AA}$  lines of the nebula superimposed. The He II 4686  $\text{\AA}$  emission line is not present in the spectrum of the nebula, either by visual inspection of the plates or on the microdensitometer tracings. The intensity of H14 is enhanced by [S III] and H 16 is enhanced by He I. The spectrum of HM Sge resembles most closely that of either NGC 7026 or IC 1747, both of which are excited by Wolf-Rayet central stars (Aller, 1968, p. 352). A high contrast print of the Aug. 18-19, 1977 observations which enhances the Wolf-Rayet features is reproduced in Plate 1.

Short term variability in the spectrum of HM Sge is exhibited by the behavior of the [Ne III] 3868  $\text{\AA}$  line as shown in Figures 2(a) and 2(b). The [Ne III] 3868  $\text{\AA}$  line is fainter than the neighboring H8 3889  $\text{\AA}$  line on Aug. 5-6, 1977 but more intense than H8 on Aug. 18-19.

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## CONCLUSIONS

The emission lines and spectral features identified in the observed spectrum of HM Sge are characteristic of a high density and moderately high excitation planetary nebula having a type WC Wolf-Rayet central star. Short term variability is shown by the behavior of the [Ne III] 3868  $\text{\AA}$  line between observations separated by two weeks. HM Sagittae therefore manifests itself as a Wolf-Rayet star of type WC exciting a gaseous envelope of material ejected during an earlier stage of evolution. The observations reported here also support earlier suggestions that HM Sge may be a proto-planetary nebula or a planetary nebula in its early stages of observability.

## ACKNOWLEDGEMENTS

A Polaroid print and microdensitometer tracing of a spectrogram of HM Sge obtained June 26-27, 1977 at CTIO by Liller (1977) was kindly made available by him to us immediately after the results of our spectrogram of July 22-23, 1977 were announced on IAU Circular 3094. The information contained in Liller's spectrogram is essentially the same as that contained in our spectrograms, minus the Hg contamination. The intensity of the [Ne III] 3868  $\text{\AA}$  line relative to H8 and H9 is comparable to that on our spectrogram of August 5-6, but supports Liller's suggestion that a collaborative effort may be advantageous, especially when spectrograms covering a longer interval of time have accumulated.

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Table 1  
Summary of Observations

Date (1977)	Expos- ure	Plate	Spectral Range	
			First Order	Second Order
July 22-23	5 min.	IIa-O, unbaked	4600-7350 Å	---
July 22-23	30 min.	IIa-O, unbaked	4600-7350 Å	---
Aug. 4-5	2 hrs.	IIa-O, baked 26 hr. at 50° C	4000-6700 Å	---
Aug. 4-5	2 hrs.	IIa-O, baked 26 hr. at 50° C	6100-7350 Å	3400-4500
Aug. 5-6	2 hrs.	IIa-O, baked 50 hr. at 50° C	6100-7350	3400-4500
Aug. 5-6	2 hrs.	IIa-O, baked 50 hr. at 50° C	4000-6700 Å	---
Aug. 18-19	1½ hrs.	IIa-O, baked 50 hr. at 50° C	4000-6700 Å	---
Aug. 18-19	3 hrs.	IIa-O, baked 50 hr. at 50° C	6100-7350 Å	3400-4500 Å

Table 2(a)  
Emission Lines in HM Sgc.

λ	Strength <sup>†</sup>	Ion	λ	Strength	Ion	λ	Strength	Ion
3683	vw	H20	4340	s	H <sub>γ</sub>	5876	s	He I
3687	vw	H19	4350	w	O II	5905	w	?
3692	vw	H18	4358	NS	H <sub>q</sub>	5913	w	He II
3697	vw	H17	4363	m	[O III]	6228	w	[K VI]
3703	w	H16+HeI	4471	m	He I	6300	w	[O I]
3711	vw	H15	4550	w	Si III	6312	w	[S III]
3721	w	H14+ SIII	4658	vw	C IV, [FeIII]	6337	vw	?
3727	w	[O II]	4669	vw	[P II]	6347	w	Si II
3734	w	H13	4701	w	[Fe III]	6354	w	?
3744	vw	*	4733	vw	[Fe III]	6364	w	[O I]
3750	w	H12	4754	w	[Fe III]	6507	w	?
3762	vw	[O III]	4861	s	H <sub>β</sub>	6548	m	[N II]
3770	m	H11	4921	w	He I	6563	s	H <sub>α</sub>
3785	vw	He I	4959	s	[O III]	6584	m	[N II]
3791	vw	O III	4972	vw	[Fe III]	6678	s	He I
3797	m	H10	5007	s	[O III]	6854	w	?
3807	vw	He I	5039	w	Si II, [Fe II]	6863	vw	?
3819	vw	He I	5151	w	[Fe III]	6881	vw	He II(?)
3835	s	H9	5161	NS	H <sub>q</sub>	6893	vw	He II(?)
3856	vw	Si II	5159	vw	[Fe III]	7003	vw	[Ar IV]
3858	vw	He II	5262	w	#	7032	vw	?
3868	s	[Ne III]	5271	m	[Fe III]	7065	s	He I
3877	vw	?	5411	w	He II	7087	vw	?
3889	w	H8+HeI	5461	NS	H <sub>q</sub>	7108	vw	?
3926	d	He I	5486	w	[Fe VI]	7135	s	[Ar III]
3933	d	?	5537	w	[Cl III]	7155	w	?
3944	d	O IV	5562	w	?	7244	vw	?
3970	s	H7	5577	NS+Neb	[O I]	7256	w	?
4026	d	HeI	5702	w	*	7279	w	?
4046	NS	H <sub>q</sub>	5718	vw	[Fe VII]	7283	m	He I
4067	w	[S II]	5755	s	[N II]	7319	s	[O II]
4077	NS	H <sub>q</sub>	5770	NS	H <sub>q</sub>	7330	s	[O II]
4101	s	H <sub>δ</sub>	5790	NS	H <sub>q</sub>			
4326	w	C III	5820	w	Cr III			

Table 2(b)  
Broad Emission Features in HM Sgc.

3400 <sup>λ</sup>	w	O III, O IV	5411 <sup>λ</sup>	w	He II
4650	s	C III	5471	w	O V
4686	s	He II	6580	w	C II

<sup>†</sup> Notes:

\*= unidentified in NGC 7027

#= unidentified in IC 4997

s= strong

m= medium

w= weak

vw= very weak

d= doubtful

NS= night sky

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## Figure Captions

Figure 1 Microdensitometer tracings of the two spectrograms of HM Sge for Aug. 18-19, 1977; the ordinate is the microdensitometer signal (proportional to density) while the abscissa is position along the direction of dispersion (proportional to wavelength).

(a) Tracing covering the spectral range 4000 Å to 6700 Å in first order.  $H_{\alpha}$ , H $\beta$ , and the conspicuous Wolf-Rayet feature at  $\lambda\lambda 4650-4686$  are labeled.

(b) Tracing covering (in mixed orders) the spectral range 6100 Å-7350 Å in first order and 3400 Å-4500 Å in second order.  $H_{\alpha}$  and the [Ar III] 7135 Å line in first order are labeled; several higher members of the Balmer series in second order are also labeled. The [O II] 7320, 7330 Å doublet in first order straddles the 3663 Å line of the Hg I 3650 Å triplet in second order. The [O II] 3726, 3729 Å doublet (in second order) is not resolved on this long exposure spectrogram.

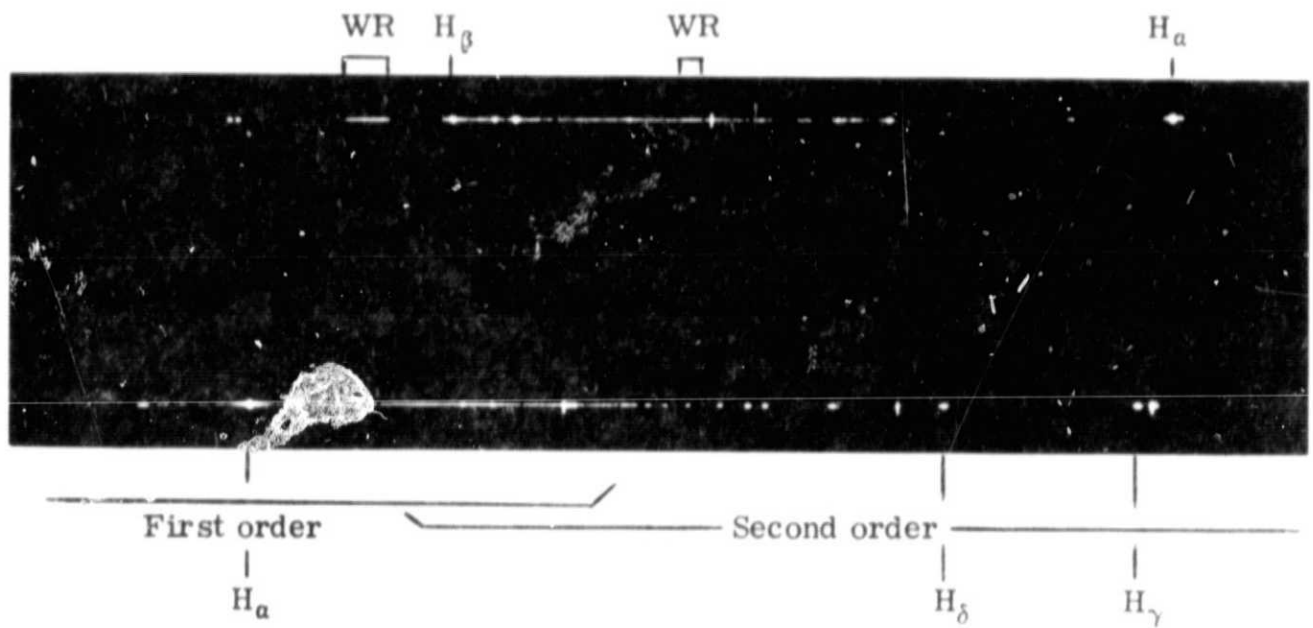
Figure 2 Microdensitometer tracings showing variability in intensity of the [Ne III] 3868 Å line relative to H8 and H9 on:

- (a) Aug. 5-6, 1977, and
- (b) Aug. 18-19, 1977.

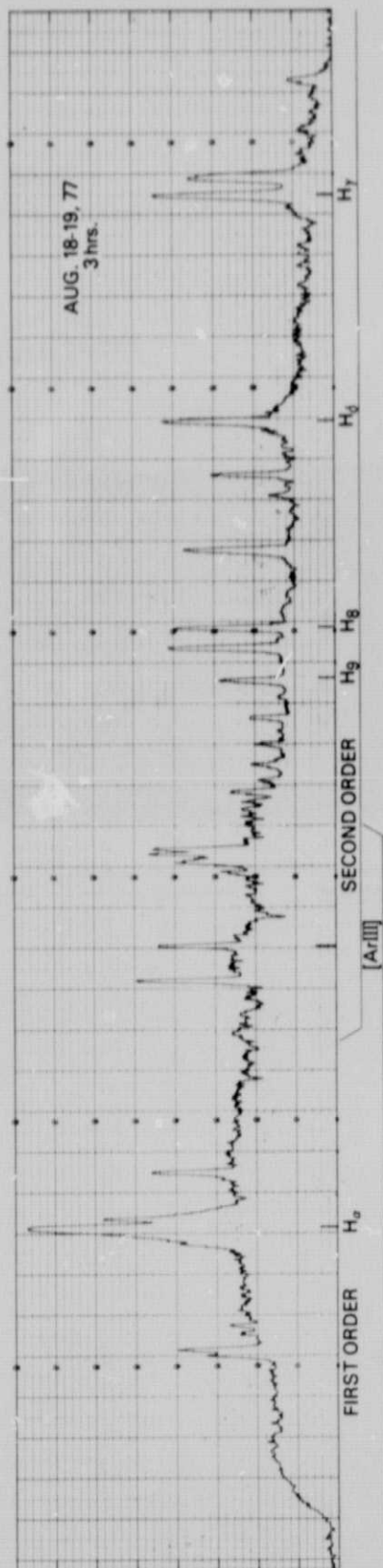
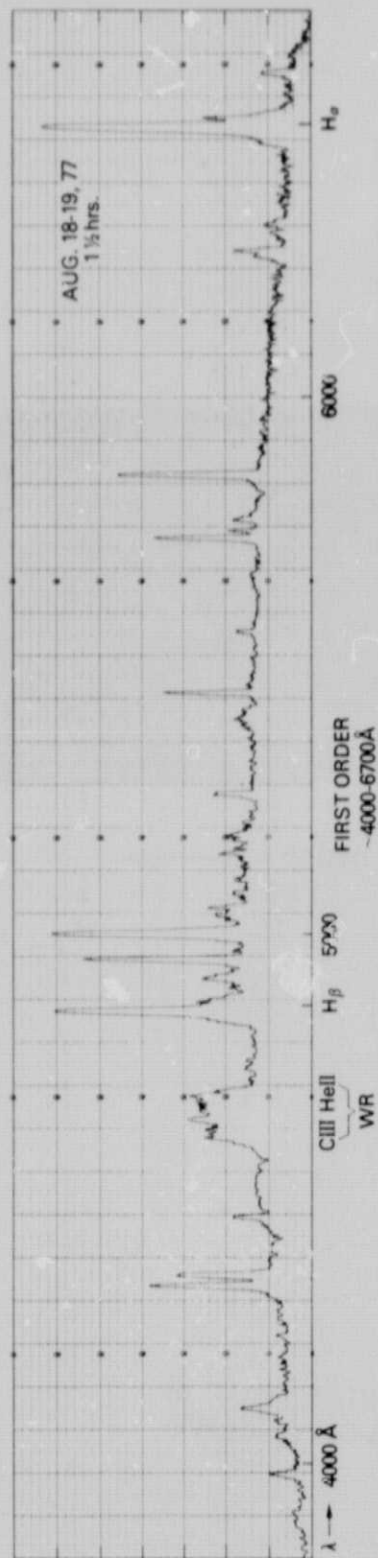
Plate 1. High contrast print of the spectrum of HM Sge. Some of the weaker emission lines are lost on this print in order to enhance the Wolf-Rayet features.

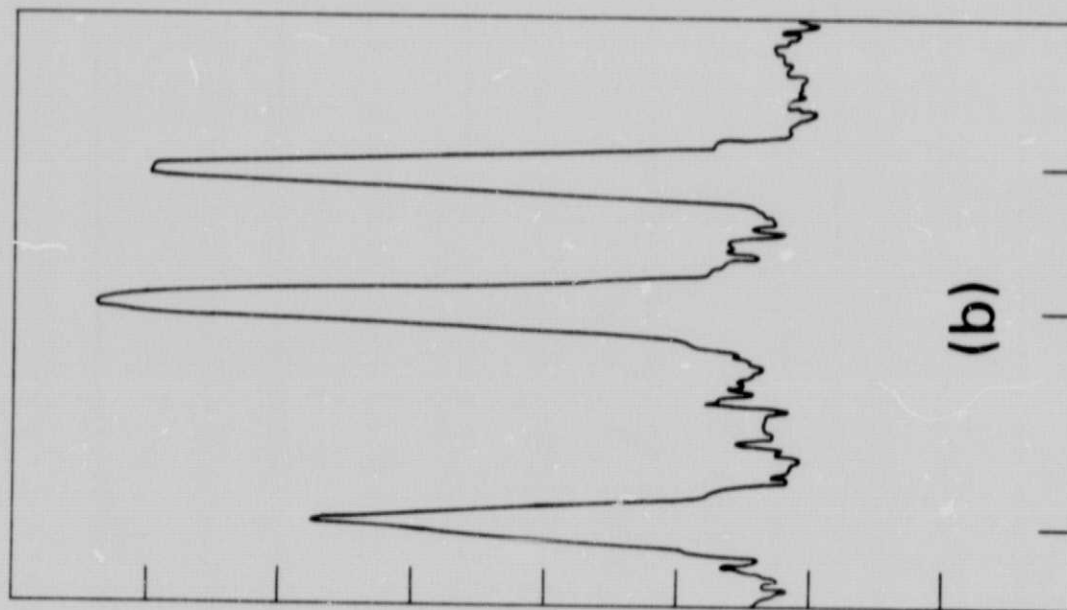
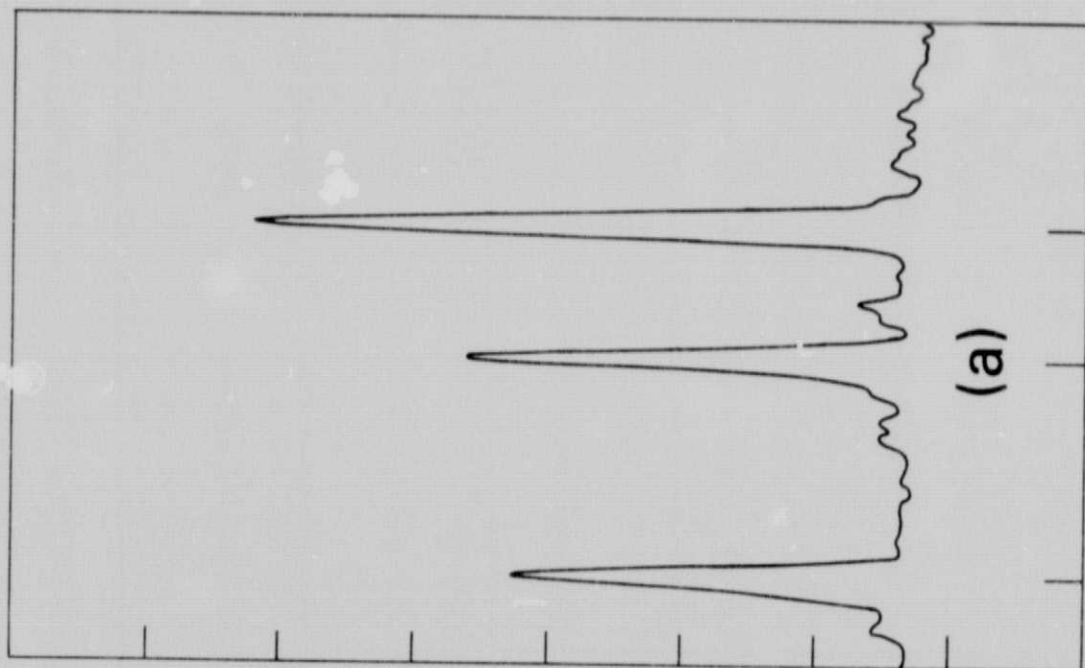
Plate 1  
Spectrum of HM Sge

First order spectrum



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